

# The effect of metallicity on the Cepheid distance scale and its implications for the Hubble constant ( $H_0$ ) determination

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**Abstract.** Recent HST determinations of the expansion's rate of the Universe (the Hubble constant,  $H_0$ ) assumed that the Cepheid Period-Luminosity relation at V and I are independent of metallicity (Freedman, et al., 1996, Saha et al., 1996, Tanvir et al., 1995). The three groups obtain different values for  $H_0$ . We note that most of this discrepancy stems from the assumption (by both groups) that the Period-Luminosity relation is independent of metallicity. We come to this conclusion as a result of our study of the Period-Luminosity relation of 481 Cepheids with 3 millions two colour measurements in the Large Magellanic Cloud and the Small Magellanic Cloud obtained as a by-product of the EROS microlensing survey. We find that the derived interstellar absorption corrections are particularly sensitive to the metallicity and when our result is applied to recent estimates based on HST Cepheids observations it makes the low- $H_0$  values higher and the high- $H_0$  value lower, bringing those discrepant estimates into agreement around  $H_0 \approx 70 \text{ kms}^{-1} \text{Mpc}^{-1}$ .

**Key words:** Stars : cepheids - Stars : fundamental parameters - galaxies : distances

## 1. Introduction

The value of the Hubble constant  $H_0$  fixes the fundamental physical scale and time scale of the Universe, therefore by inference its age. Dichotomous results are obtained in discordant ranges, even allowing for their internal error estimates. The results are dependent upon the choice of the cosmological distance ladder used (Fukugita et al., 1993, Freedman et al., 1996, Saha et al., 1996). However, both the longer distance scale ( $H_0 \approx 50 \text{ kms}^{-1} \text{Mpc}^{-1}$ ), and the shorter distance scale ( $H_0 \approx 80 \text{ kms}^{-1} \text{Mpc}^{-1}$ ) rely strongly on the Cepheid period-luminosity relation calibrated in the Large Magellanic Cloud (LMC), and assumed to be independent of metallicity. The Cepheid Period-Luminosity (PL) relation is widely considered to be the most accurate way available to measure extragalactic distances on small scale. The Cepheids are relatively young, bright periodic variable stars which pulsational periods are strongly correlated with their luminosity. Their distance is therefore determined via a comparison to a calibrated PL relation. Cepheids are observed in distant galaxies, up to the Virgo cluster, in order to calibrate secondary distance indicators that connect to the Hubble flow.

The theory (Stothers, 1988, Stift 1990, Chiosi et al., 1993, Stift 1995) predicts a small abundance (helium fraction and heavy elements) effect on the PL zero point due to: (i) theory of stellar pulsation through the dependence of period on mass and radius. (ii) theory of stellar evolu-

tion through the mass luminosity relation. (iii) theory of stellar atmosphere through the relation between effective temperature, absolute magnitude in bandpasses and bolometric correction. Disentangling the effects of metallicity and reddening has a venerable history (Feast 1991). Various observational studies since the 70s, have looked for and found a color shift between LMC and SMC Cepheids (e.g. Gascoigne 1974, Martin et al. 1979). Caldwell & Coulson (1986) and more recently Laney & Stobie (1994) used theoretical and empirical relations, as well as individual reddenings from color-color diagrams to derive PL relations adjusted for abundance differences. Their approach is different from ours (and the technique used by the *HST* teams); a full comparison will be model dependent (flux redistribution models) and we have not attempted to do that here. A limited comparison to the VJHK Table 6 of Laney & Stobie (1994) shows that we confirm the sense of their results.

An empirical test (Freedman and Madore, 1990, Gould, 1994) in three fields of M31 with 36 Cepheids and 152 BVRI measurements have led to ambiguous results. As part of the HST key project on extragalactic distance scale observations, a further check is planned by observations of two fields in M101. Currently, all HST studies assume that the Cepheid PL relation has no metallicity dependence (Freedman et al., 1994a, Freedman et al., 1994b, Sandage et al., 1994, Tanvir et al., 1995, Kennicutt et al., 1995).

## 2. EROS observations.

We used a new data set of 481 Cepheids and 3 millions measurements in two colours obtained in the LMC and the SMC to derive the dependence of the optical period luminosity relations on metallicity. Observations were obtained as a by-product of the EROS (Expérience de Recherche d'Objets Sombres, Aubourg et al., 1993) microlensing survey.

Observations have been obtained from ESO La Silla using a 0.4m f/10 reflecting telescope and a  $2 \times 8$  mosaic of CCDs (Arnaud et al., 1994ab). During the  $\sim 100$  nights of 1991-1992 campaign (Beaulieu et al., 1995, Grison et al., 1995), about 2000 images have been obtained in the bar of the LMC in a blue and a red bandpass ( $B_E$  and  $R_E$ ), whereas about 6000 images have been obtained in a crowded field of the SMC with a near pair of very similar filters ( $B_{E2}$  and  $R_{E2}$ ) during the  $\sim 200$  nights of 1994-1995 season (Beaulieu et al., 1996). An accurate and reliable photometric transformation have been constructed between the two systems. Hence we present a differential analysis that relies on no external zero-point and thus completed within the ( $B_E$  and  $R_E$ ) system. Since we apply our result to HST  $V$ ,  $I$  observations, we make use of the fact that the net transmission of the  $B_E$  band after convolution with the CCD response is much closer to Johnson  $V$  than to Johnson  $B$ . The transformation is similar to that

between the broader *HST* F555W filter and  $V$ . The  $R_E$  band is between Cousin  $R$  and  $I$ . The  $B_E - R_E$  color transforms well to  $V - I$ :  $V - I = 1.02(B_E - R_E)$ ,  $\sigma = 0.02\text{mag}$ .

The two data sets were searched for Cepheids with Fourier analysis (Grison 1994) and phase dispersion minimisation techniques (Schwarzenberg-Czerny 1989). Stars affected by blending effects have been excluded of the sample. The high quality, excellent phase coverage light curves were Fourier analysed to separate between the classical Cepheids that pulsate in the fundamental mode, and the so called s-Cepheids that pulsate in the first overtone, and therefore follow a different period luminosity relation. In the LMC we keep 51 fundamental pulsators and 27 first overtone pulsators, and 264 fundamental pulsators and 141 first overtone pulsators in the SMC. So, we have two complete samples of Cepheids that fill densely the period-magnitude-color [PLC] space, with known difference in metallicity  $\Delta[Fe/H]_{LMC-SMC} = 0.35$  (Spite and Spite, 1991, Luck and Lambert 1992).

## 3. The method

We compare the two samples in the PLC manifold to derive 2 independent sources of difference – distance and extinction, and to search for a third one – metallicity. The method will be applied independently to both fundamental and first overtone pulsators, and is a  $\chi^2$  minimization fit to a model. Details of the method are presented elsewhere (Sasselov et al., 1996). The model is built on the basis of the technique used for determining Cepheid distances to galaxies by the *HST* Key Project (Freedman and Madore, 1990). It is as follows: the LMC PL relation is used to slide the observed PL relation against it; the Galactic extinction law is applied in deriving the reddening (implicitly assuming *no* difference between the ensemble colors of the Cepheids in LMC and the observed galaxy); a true distance modulus is derived by adopting a LMC distance and correcting for extinction (using the reddening derived above with adopted LMC reddening  $E(B-V)=0.10$ ). Other assumptions in the technique (and our model) are: constant PL slope with metallicity (confirmed by our observations) and no depth dispersion in the LMC Cepheid sample (which is only from the LMC bar). In the application we use as constraints the independently derived foreground reddening of LMC (0.06) and SMC (0.05), and the line of nodes for SMC from Caldwell & Coulson (1986) to derive the EROS SMC sample depth dispersion. We fit for different fixed values of the extinction parameter  $R_V$ . The model describes the case considered by Stothers (1988) in his equation (26).

We model the  $B_E$ ,  $R_E$  data in the PLC space taking into account the high degree of correlation between the measurements following the formalism introduced by Gould (1994). Unlike Gould, we solve for a wavelength dependance of a metallicity effect. Our model has 12 parameters, which are : linear fits of the correlations in the

PLC projections (slopes  $\beta_i, b_i$  and the zero points  $\alpha_i, a_i$ ), the distance difference  $\gamma_1$ , the relative reddening difference  $\gamma_2$ , and the metallicity terms  $\gamma_3^i$  ( $i=1,2$  are the two passbands,  $B_E$  and  $R_E$ ). The model parameters are estimated by minimizing the mean magnitude residuals,  $X_{i,p}$ , where  $Q_{i,p}$  is the observed mean magnitude in the  $i$  band for a Cepheid with period  $P_p$ . For example, the residuals for the SMC sample are given as:

$$X_{i,p}^3 = Q_{i,p} - (\alpha_i + \beta_i \log P_p + \gamma_1 + \gamma_2 R_i + \gamma_3^i), \quad (1)$$

$$X_{i,p}^4 = Q_{i,p} - [a_i + b_i(Q_{1,p} - Q_{2,p} + \gamma_2(R_2 - R_1) + \gamma_3^1 - \gamma_3^2) + \gamma_1 + \gamma_2 R_i + \gamma_3^i], \quad (2)$$

with  $p = 1, \dots, N(n)$  being the number of Cepheids. The form of the covariance matrices of the data, the  $\chi^2$  minimization and the iteration procedure are described in Saselov et al. (1996).

#### 4. The results

We applied the global fitting procedure to the data-set of fundamental mode and first overtone mode pulsators independently, and we obtained the same results.

The two set of PL relation give, before correction for metallicity and reddening, the same distance modulus difference of  $\delta(LMC - SMC) = 0.89 \pm 0.05 \text{ mag}$ . The other model parameters have the following values for the fundamental pulsators:  $\alpha_i, \beta_i = 17.61 \pm 0.035, -2.72 \pm 0.07$ ;  $17.74 \pm 0.029, -2.95 \pm 0.06$ ;  $a_i, b_i = 14.49 \pm 0.13, -11.78 \pm 0.94$ ;  $14.36 \pm 0.12 - 12.77 \pm 0.90$ .  $\gamma_1 = 0.62 \pm 0.04, \gamma_2 = 0.01 \pm 0.01, \gamma_3^1 = 0.06 \pm 0.01, \gamma_3^2 = -0.01 \pm 0.01$ . We adopted the same extinction law with  $R_V = 3.3$  for the SMC. The correction due to the metallicity dependence of the inferred distance modulus by the described technique is then  $\delta\mu = \Delta\mu_{true} - \Delta\mu_{inferred} = -0.139_{-0.06}^{+0.04} \text{ mag}$ .

The sources of error are the photometric transformation, between the two data sets (0.06 mag), the scatter in the PL relation (0.04 mag) and the uncertainties in the reddening and depth determination in the SMC (0.03 mag).

An alternative to the metallicity effect could be unusual SMC extinction with a value of  $R_V \geq 5$  and  $E(B - V) \leq 0.04$ . We consider this alternative to be very unlikely, because it requires that the extinction be less than the foreground to SMC and an unusually high  $R_V$  value unjustified by any other evidence. On the other hand, with  $R_V = 3.3$ , our mean reddening value is in good agreement with a number of other independent estimates (Bessell 1991).

We derive the following metallicity dependence of reddening corrected distance moduli of Cepheids:

$$\delta\mu = (0.44_{-0.2}^{+0.1}) \log \frac{Z}{Z_{LMC}},$$

where  $Z$  is the abundance of heavy elements (by mass) in the studied Cepheids and  $Z_{LMC} = 0.0085$ . The metallicity dependence is valid in the spectral region covered by the EROS filters, but can be applied to HST (V,I) work for the reasons presented in Sect.2 above. The form of the metallicity dependence used here is based on theoretical considerations and is a good assumption in the suggested range of application of  $0.001 \leq Z \leq 0.02$  (Chiosi et al. 1993).

Despite its relative weakness, this metallicity effect is significant to extragalactic distance measurements. This is especially true when the color shift due to metallicity  $\gamma_3^1 - \gamma_3^2$  is interpreted as reddening in the determination of the true distance modulus of a target galaxy (Freedman et al., 1994a, Freedman et al., 1994b, Sandage et al., 1994, Tanvir et al., 1995, Kennicutt et al., 1995).

#### 5. Effect on $H_0$ determination

Recent efforts to determine  $H_0$  from Cepheid distances have focused on: (1) the Virgo cluster galaxies (Freedman et al., 1994a), (2) the Leo I group (Tanvir et al., 1995), containing elliptical galaxies; and (3) the parent galaxies (Sandage et al., 1994) of supernovae of type Ia. All these studies use the same modern technique with the LMC as a base and all the same initial assumptions; we share them in our analysis. Yet they result in three different values of  $H_0$ , with hardly overlapping error bars. The abundances of metals in the young populations of the host galaxies for these studies differ and, apparently, in a systematic way. Therefore we propose that the metallicity dependence may be responsible for most of this discrepancy.

With the first approach and HST VI photometry of Cepheids in M100, they derive  $H_0 = 80 \pm 17 \text{ km.s}^{-1} \text{ Mpc}^{-1}$ . For the metallicity of the Cepheids we adopt  $[\text{Fe}/\text{H}] = +0.1$  ( $Z=0.02$ ), derived from the abundances of

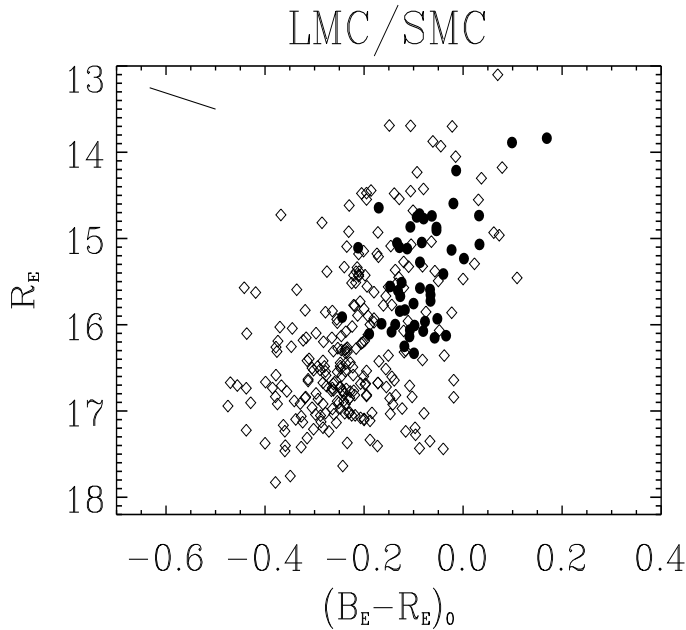
H II regions (Zaritsky et al., 1994) and assuming a solar  $[\text{O}/\text{Fe}]$  ratio. With the uncertainty range of our metallicity effect, this leads to  $H_0 = 76 - 70 \text{ km.s}^{-1} \text{ Mpc}^{-1}$ .

With the second approach and HST VI photometry of Cepheids in M96 (Tanvir et al., 1995), they derive  $H_0 = 69 \pm 8 \text{ km.s}^{-1} \text{ Mpc}^{-1}$ . Oey & Kennicutt (1991) give an abundance estimate for M96 of  $[\text{Fe}/\text{H}] = -0.02$ . This implies a small change in the Cepheid distance to M96 and the value of  $H_0$ ,  $H_0 = 64 - 66 \text{ km.s}^{-1} \text{ Mpc}^{-1}$ .

With the third approach and HST VI photometry of Cepheids in IC4182 and NGC5253 (Sandage et al., 1994), they derive  $H_0 = 55 \pm 8 \text{ km.s}^{-1} \text{ Mpc}^{-1}$ . Abundances in NGC5253 have been measured and discussed (Pagel et al., 1992); discussion of abundances in IC4182 has been also given by Saha et al., (1996) — we adopt  $[\text{Fe}/\text{H}] = -1.3$  and caution on the large uncertainties. With this metallicity  $H_0 = 59 - 68 \text{ km.s}^{-1} \text{ Mpc}^{-1}$ . Other systematic effects in the SN Ia method (Riess et al., 1995), bring the value of  $H_0$  even further up; to a value also favored by new

theoretical SN models (Höflich and Khokhlov 1996). The new value of  $H_0 = 58 \pm 4 \text{ km.s}^{-1} \text{ Mpc}^{-1}$  (Sandage et al., 1996) includes two SNe Ia in spiral galaxies, which Cepheid metallicity is most likely similar to that of the LMC. Note, however, that the two SN (1981B and 1990N) are by 0.2–0.4 *mags* dimmer than the three SNs in IC4182 and NGC5253. Therefore, the result we obtained above by accounting for the effect of metallicity on the Cepheid distances for each galaxy, remains virtually unchanged.

The metallicity dependence we found from the LMC/SMC analysis brings all the derivations of  $H_0$  to good agreement. It is summarized in Fig. 2.

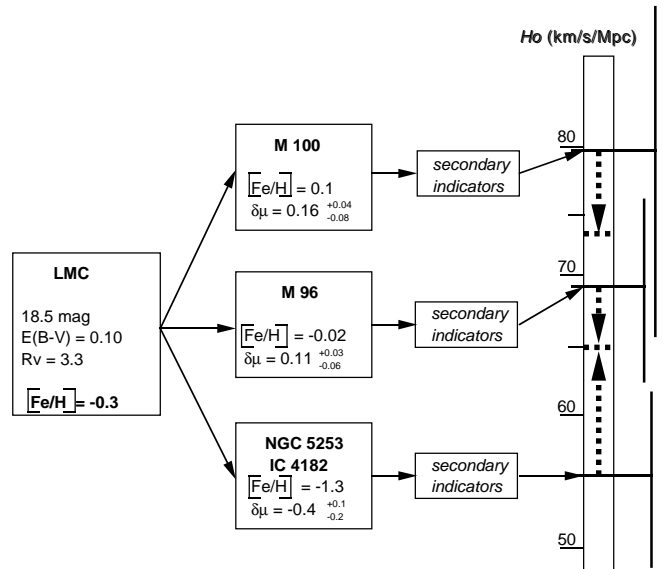


**Fig. 1.** The colour magnitude diagram for the fundamental mode Cepheid pulsators in the SMC (diamond) and LMC (filled diamond) in the  $B_E - R_E$  colour system. The difference vector represents the reddening line in this plane. The color difference between the two samples of Cepheids is due to their different metallicity. The SMC Cepheids are bluer and fainter at a given pulsation period.

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**Fig. 2.** Metallicity effect on the Cepheid extragalactic distance scale and its influence on HST observations of distant galaxies : all these  $H_0$  determination are brought into good agreement. the quoted uncertainty in  $\delta\mu$  comes from our uncertainty of the metallicity effect. We do not include uncertainty in  $[\text{Fe}/\text{H}]$ .

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